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Ecological and Economic Implications of Establishing Quercus spp. in the Urban Environment

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Ecological and economic implications of establishing *Quercus* spp. in the urban environment

A Thesis Presented

by

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ABSTRACT

ECOLOGICAL AND ECONOMIC IMPLICATIONS OF ESTABLISHING *QUERCUS* SPP. IN THE URBAN ENVIRONMENT

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As urban greening efforts continue, it is important to assess whether decisions to intensify street tree planting are meeting intended goals of improving urban canopy cover and increasing ecosystem services. Benefits of the urban forest take many forms, from ecological and economic to social and cultural, and are frequently cited in support of street tree planting. However, it is unknown to what extent factors such as species or nursery production method affect the ability of trees to successfully establish and provide ecosystem services in the urban environment. Using a system of oak trees planted along roads in South Amherst, Massachusetts during spring 2014, growth in caliper at six inches, diameter at breast height, and total tree height from fall 2014 to fall 2018 were modeled to determine whether species and/or nursery production method influenced street tree establishment and growth. Economic benefits were examined using a novel approach, whereby the breakeven point of costs and returns in ecosystem services was identified. Results indicated that both species and nursery production method influenced the success of these trees, which provided a return on investment by year 2018, in terms of both growth and benefits provided. This information is relevant to tree wardens and others tasked with street tree planning and maintenance, who must work within the confines of limited budgets in an environment that poses many challenges for trees.

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OAK TREES IN THE LANDSCAPE: RURAL AND URBAN

Cultural and historic significance

"Neither layman nor botanist though is likely to be aware of the full extent of cultural influence the wood has had: in architecture, beliefs, communications by land and sea and in writing, drinking and eating, the environment, as a resource to be used and conserved, the impact of its scarcity on individual trades and national standing, and much more." (Young 2013, p. 20)

Comprised of nearly 60 species native to the U.S. alone, oak trees are the most widespread hardwoods in the temperate zone of the northern hemisphere (Arbor Day Foundation 2019). There are somewhere between 600 and 800 species of trees and shrubs belonging to the genus *Quercus*, though hybridization makes it difficult to be more precise (Young 2013). Oaks are not necessarily the most remarkable trees, but they are ubiquitous, taking both deciduous and evergreen forms. Given their broad distribution across the natural landscape, it is no wonder that they percolate nearly every facet of human culture, from food and drink to literature, art, and history (Logan 2005; Young 2013).

"What's in a name?"

The dominance of oak trees and their influence is first and foremost obvious in nomenclature. Oak is the most widely used tree name among Western languages (Logan 2005). Places, surnames, occupations, and nicknames are oak-derived. For example, there is Oakland, California, which alludes to over 20 native species of oak that occur throughout the state (Costello et al. 2011). German place names like Eichendorf and

Eichsfeld, among others, implement the German word for oak: *Eiche* (Young 2013). In addition, names with the roots *ac, ech, ag, og, hick, heck, chene, cas, daru, dru*, and *rove* are attributed to oak origin (Logan 2005). Common surnames include Oakford, Oakham, and Oakhill or, in Estonia, Tamm, which is a direct translation of oak (Logan 2005; Young 2013). Where oak trees have grown, so did their influence in the names and lifestyles of those that depended on them.

Oak wood products

The wood of oak trees has served many uses throughout time and across societies. Strong, watertight, and workable, oak trees were often preferred for shipbuilding (Logan 2005). The Vikings crafted many of their notorious longships out of oak (Figure 1), and other European peoples followed suit (Logan 2005; Young 2013). The *USS Constitution* was made from 1500 oak trees; white oak (*Q. alba*) from New England and live oak (*Q. virginiana*) from the Georgia sea islands can be credited with earning the ship's nickname, "Old Ironsides," having successfully repelled British cannonballs (Arbor Day Foundation 2019; Logan 2005).

Figure 1. The Oseberg longship, a Viking artifact constructed almost entirely out of oak. Photo credit to BBC (https://www.bbc.com/bitesize/articles/zw3qmp3).

In addition to ships, oak trees made their mark in the joints and frames of buildings, with artistic flare arising through wooden architecture. Perhaps the most notable contribution of the European Middle Ages is the 660-ton, hammer-beam roof of Westminster Hall (Figure 2) in London's Houses of Parliament (Logan 2005; Young 2013). On a smaller scale, oak wood was used to create furniture and hand tools (Young 2013), and, to this day, it is a popular choice for wine barrels and liquor casks (Logan 2005).

Figure 2. The hammer-beam oak roof of Westminster Hall, Palace of Westminster, London. Photo credit to Donald Insall Associates (https://www.donaldinsallassociates.co.uk/projects/palace-of-westminster-westminster-hall/).

Byproducts from oak trees, both well- and lesser-known, include leather and ink, respectively. The word "tan" is derived from the Latin for oak bark (Logan 2005), which is used for tanning hides to make leather. When ground fine and soaked in water, the bark releases tannins, which prevent the hides from decaying while creating a supple and waterproof material (Logan 2005; Young 2013). Additionally, tannin has been used for dyes and ink. The tannins that produce dyes are found in galls caused by wasps, which appear to neither help nor harm their host trees, except in extreme circumstances. The ink oak, *Quercus tinctoria*, is named for its use in ink making (Logan 2005). When combined with a binder, such as naturally-occurring gum arabic (i.e., acacia sap), the ink fixes readily to parchment (Young 2013). The U.S. Constitution and Declaration of

Independence, Leonardo da Vinci's drawings, and Bach's music were all drafted with oak gall ink (Logan 2005).

Oak symbolism and historic trees

"With something as widely dispersed, geographically and historically, as the oak, its meaning has become diffuse." (Young 2013, p. 127)

Beyond the use of oak ink for writing and drawing, the oak tree itself is a common and consistent figure in stories and art, symbolic across nations, cultures, and religions. Oaks are featured in folklore and mythology, poetry and proverbs, classic pieces of literature, and even slang (Young 2013). The oak tree is the most sacred tree in Celtic beliefs, its roots allegedly the door to the Otherworld. Accordingly, the Celtic name for oak is *daur*, the origin of the word "door" (Symbol Dictionary 2019; Young 2013). Oaks are prominent in paganism, often regarded as sacred by mythological gods of thunder and lightning, such as Thor (Young 2013).

Oak trees are national symbols in England, France, and Germany, appearing on currency, official uniforms, logos, and family coats of arms (Young 2013). The oak tree is the national tree of many countries, including the U.S., where oaks overwhelmingly defeated other candidates in a 2004 vote of people's choice for America's national tree (Arbor Day Foundation 2019). Oak species are the official tree of six U.S. states, including Connecticut, Georgia, Illinois, Iowa, Maryland, and New Jersey, as well as Washington, D.C. (Breyer 2017). Beyond symbols, they have served as landmarks and places of refuge for many peoples, including historic figures. Abraham Lincoln used the

Salt River Ford Oak to navigate a river crossing near Homer, Illinois (Nadkarni 2008), while Robin Hood was sheltered by oaks in Sherwood Forest (Stafford 2016).

The tales of Robin Hood, his Merry Men, and their forest hideout became associated with a famous English or penduncculate oak (*Q. robur*) in Nottinghamshire, England, called the Major Oak (Figure 3). Voted England's first-ever "Tree of the Year" in 2014, it is thought to be between 800 and 1,000 years old (Klein 2016; Visit Nottinghamshire 2019). King Charles II also sought shelter in an oak, which concealed him after his defeat at the Battle of Worcester during the English Civil War in 1651 (Logan 2005; Young 2013). A symbol of American independence, the Charter Oak in Hartford, Connecticut was used by the colonists to hide the state's charter from King James II (Young 2013; Rutkow 2012). The white oak, which failed in 1856, was officially mourned and remains the state tree to this day (Logan 2005).

Figure 3. The Major Oak, an English oak tree (*Q. robur*) propped up by steel poles in the Sherwood Forest of Nottinghamshire, England. Photo credit: Visit Nottinghamshire (https://www.visit-nottinghamshire.co.uk/things-to-do/the-major-oak-p586841).

Balanophagy

Balanophagy: the practice of eating acorns (Starin 2014). It is proposed that acorns might have been a staple of the hunter-gatherer diet (Logan 2005; Starin 2014). Easy to collect, store, and process, with many nutritional benefits, acorns were used historically to feed humans and their livestock, especially hogs in Europe (Bainbridge 1986; Logan 2005; Starin 2014; Young 2013). They appear in Greek and Roman written records, with the old Tunisian word for oak meaning "meal-bearing tree" (Logan 2005). Acorns were particularly important as a food crop in California, where Native Americans harvested and consumed them for millennia (Prichep 2014; Starin 2014). They are also common in Korean markets, where they may be sold as starch flour, acorn jelly, or acorn noodles (Bainbridge 1986; Prichep 2014; Young 2013).

Though tannins must be leached during preparation, acorns are a source of proteins, fats, carbohydrates, and minerals (Bainbridge 1986; McShea and Healy 2002; Miller and Lamb 1985; Ocean 2006). As such, they are good for maintaining low blood sugar levels, in addition to being lower in saturated fats than most other nuts (Young 2013). Today, there is interest in reintroducing acorns to the human diet; recipe books and online resources detail how to sustainably collect and properly prepare them before cooking. Acorns may be roasted and eaten alone, though they were often used to fill out recipes, especially when grain was not available. Thus, they are growing in popularity as flour and becoming more common in baked goods, as well as soup (Logan 2005; Ocean 2006; Shaw 2019; Stillman et al. 2018).

Oaks and wildlife

Beyond their significance to people, oak trees are a major component of wildlife habitat; they provide structure for cover and nesting sites and supply acorns, which are an important food source for many wildlife species across taxa, including mammals, birds, and insects (Miller and Lamb 1985; Martin et al. 1951; McShea and Healy 2002). Van Dersal (1940) identified 186 birds and mammals in the U.S. that utilize oak products, including acorns. Acorns rank at the top of the food list for wildlife in large part because of their abundance, especially during the winter, when other food items are scarce (Miller and Lamb 1985; Martin et al. 1951). Martin et al. (1951) estimated that over 96 species in the U.S. consume acorns, while Miller and Lamb (1985) asserted that 49 of those species are found in the eastern U.S. alone. Deer, black bear (*Ursus americanus*), and turkey (*Meleagris gallopavo*) are heavily dependent on acorns, which comprise upwards of 50 to 75% of their diets (Martin et al. 1985). Such strong associations with this food source influence the distributions of deer, black bears, and other species (McShea and Healy 2002).

Some interesting interactions and cycles occur among wildlife, oak trees, and acorns. During mast years, when oaks produce greater quantities of acorns, there are increased populations of white-footed mice (*Peromyscus leucopus*) and presence of white-tailed deer (*Odocoileus virginianus*) in oak-dominated forests. Greater densities of both species in time and space increase the likelihood for transmission of Lyme disease, whereby white-tailed deer harbor adult black-legged ticks (*Ixodes scapularis*), also known as deer ticks, which are most likely to acquire the Lyme disease bacterium via white-footed mice in their larval stage (McShea and Healy 2002; Ostfeld et al. 1998).

Consequently, there is increased probability of Lyme disease transmission following heavy acorn production, when ticks and mice co-occur in greater numbers. White-footed mice are also known to consume gypsy moth (*Lymantria dispar*) caterpillars, helping to regulate populations of this invasive oak forest defoliator when it occurs in low densities (Jones et al. 1998; McShea and Healy 2002; Ostfeld et al. 1996).

Other common consumers of acorns include squirrels, jays, and weevils. Both squirrels and jays cache acorns, recovering some while leaving many more in the ground to germinate (Logan 2005; McShea and Healy 2002). The acorn woodpecker (*Melanerpes formicivorus*) of the Western and Southwestern U.S. is another caching species, notorious for storing acorns in granary trees (Cornell Lab of Ornithology 2017). The eastern gray squirrel (*Sciurus carolinensis*) demonstrates an interesting behavior in how it handles acorns from the two oak subgenera, the red oak group (subgenus *Erythrobalanus*) and the white oak group (subgenus *Leucobalanus*). Though white oak acorns have less nutritional value, they are preferred by most wildlife species (humans included) over red oak acorns, which have higher concentrations of bitter tannins that are more difficult to digest (Chung-MacCoubrey et al.1997; Ofcarcik and Burns 1971). Another noteworthy difference between the subgenera is that white oak acorns germinate in the fall, while red oak acorns overwinter and germinate in the spring (Fox 1982). In response, eastern gray squirrels are known to immediately consume acorns from the white oak group and cache those from the red oak group. White oak acorns may be cached, but only after removing the embryo of the seed. This halts the germination process, allowing the squirrel to later capitalize on the nutritional resources that would be otherwise utilized during germination (Fox 1982; Hadj-Chikh et al. 1996).

Jays are one of the greatest vectors of oak dispersal and propagation (Gómez 2003), caching more than 4,500 acorns or more in a given year (DeGange et al. 1989), sometimes up to a mile away from the source tree (Darley-Hill and Johnson 1981), and recovering only one in four nuts (Logan 2005). They are even credited with the rapid recolonization of oaks following the last glacial retreat in North America and Europe (Harper et al. 2019; Logan 2005). Acorn-dispersing jay species include the European jay, *Garrulus glandarius* (Gómez 2003), blue jay, *Cyanocitta cristata*, (Darley-Hill and Johnson 1981), and Florida scrub jay, *Aphelocoma coerulescens* (DeGange et al. 1989.) The physiology of jay species is tied to their dietary needs, with bills adapted to tearing husks and hammering acorns into the ground (Logan 2005). Breeding is also timed with acorn availability, and the innate ability of jays to remember landscape features can be attributed to caching behavior (Clayton and Dickinson 1998; Clayton et al. 2003; Logan 2005).

Another wildlife species adapted to the oak nut is the acorn weevil, an insect belonging to the snout beetle family, Curculionidae. Acorn weevils may have long (Figure 4) or short snouts, called rostrums, which are used to bore through acorn shells to feed and lay eggs inside the nutmeat (Red Planet 2018).

Figure 4. Acorn weevil (*Curculio glandium*), featuring a long rostrum used to bore into acorn shells to consume nutmeat and lay eggs. Photo credit: Graham Calow (https://www.naturespot.org.uk/species/acorn-weevil).

Females have longer rostrums than males and deposit short, cylindrical larvae into acorns, where they feed and eventually bore their way out (NatureSpot 2019). Acorns are subjected to heavy weevil damage, often rendering the seeds incapable of germinating or slowing growth (McShea and Healy 2002; Miller and Lamb 1985). Acorn weevils are not the only insects to exhibit a peculiar relationship with oak trees. As mentioned previously, cynipid wasp species form galls on oaks. Galls (Figure 5) are essentially growths comprised of plant tissue that occur in response to a chemical secretion produced by gall wasp larvae (Penn State 2019). These growths form around the larvae, housing them until they become adults; self-fertile adult females lay their eggs elsewhere on the host and repeat the process (Logan 2005). Some galls produce their own honeydew, which is fed upon by ants. The ants defend the galls against predators, namely parasitoids, that would eat the wasp larvae or take over the gall for their own broods (Logan 2005; Washburn 1984).

Figure 5. Galls produced from cynipid wasp larvae on a white oak tree. Photo credit: SFGate, Hearst Newspapers, LLC (https://homeguides.sfgate.com/rid-oak-galls-37878.html).

Oak trees are a major component of wildlife habitat, especially in Northeastern U.S. forests. Like wasp and weevil larvae, oak trees host varying life stages of many other insects. They are particularly important for Lepidoptera species; Tallamy and Shropshire (2009) found that the genus *Quercus* supports over 530 species of butterflies and moths, placing first in a ranking of most valuable plant genera for lepidopteran hosts. Over 190 wildlife species utilize red oak (*Q. rubra*) forests in New England alone (DeGraaf and Yamasaki 2001), for any combination of feeding, cover, nesting, and breeding. With such prevalence and significance in the natural landscape, it becomes much simpler to identify why oak trees have a place among urban infrastructure in human-dominated environments.

Urban oak trees

Though the practice and profession of forestry has a longstanding history, urban trees and forests were not managed in the U.S. until the late 1800s. The roots of Arbor Day were founded in 1872 by J. Sterling Morton, and tree planting traditions bloomed thereafter (Jonnes 2016; Miller et al. 2015). Canadian forestry professor Erik Jorgensen is credited with coining the term “urban forest” in 1965 (Jonnes 2016), but urban forestry was not formally recognized as a discipline within the forestry profession until the 1970s (Miller et al. 2015). By 1990, the U.S. Forest Service’s Urban and Community Forestry Program finally achieved a line-item spot within the Farm Bill, dramatically increasing the program’s funding (Jonnes 2016). Much of the commitment to urban forestry practices may be attributed to the devasting effects of pests and diseases, especially Dutch elm disease (DED). Elm trees were once considered *the* superior shade tree, revered across America for their shape, stature, and ability to tolerate harsh urban conditions (Jonnes 2016). Following their collapse to DED, oak trees arose as a plausible alternative for urban foresters looking to replace their beloved elms. In an issue of *Arnoldia*, the journal of the Arnold Arboretum, dedicated to replacement trees for the American elm, authors described red oaks as excellent street trees, “tolerant of poor, dry, compacted soils, salt, and atmospheric pollution” that are capable of withstanding “the inevitable impact of vehicles" (Jonnes 2016). This brings us to one of the main characters in our study system, the red oak.

The northern red oak, *Quercus rubra*, is a stately tree that grows to be 20 to 30 meters tall (Miller and Lamb 1985). It is one of the most widely distributed oak species in North America, where it is commonly planted as a landscape tree (Nesom 2009a). This fast-growing species can withstand dry, acidic soil conditions, as well as air pollution; red oaks also exhibit some tolerance to salt (Nesom 2009a; Urban Horticulture Institute 2009). They are often valued for their red foliage in the fall (Figure 6), though this characteristic varies with cultivars (Costello et al. 2011). Since red oak trees can grow quite large, selection in the urban landscape must consider whether there is enough space for their mature form.

Figure 6. Immature northern red oak (*Quercus rubra*) featured in bright red fall color (front left). Photo credit: Perennial Nursery Co. (https://www.perennialco.com/northern-red-oak/).

While neither as large or fast-growing as the red oak, the other species in our system is the swamp white oak, *Quercus bicolor* (Figure 7). Swamp white oaks are medium-sized trees that typically grow to 20 meters tall (Miller and Lamb 1985; Urban Horticulture Institute 2009). Their crowns may be poorly formed or irregular (Miller and Lamb 1985), though this can be mitigated by proper pruning techniques. Fall color is yellow or occasionally red-purple (Nesom 2009b). Swamp white oaks are especially valued in the urban landscape because they are easily transplanted and can tolerate varying soil moisture conditions, from periods of drought to inundation with water (Urban Horticulture Institute 2009). They are tolerant of acidic soils and significant levels of compaction, and their acorns are highly valued by wildlife (Nesom 2009b).

Figure 7. Mature swamp white oak (*Quercus bicolor*) in fall foliage. Photo credit: Landmark Nursery and Landscaping (https://landmarklandscapes.us/plants-database/trees-sale/99a-swamp-white-oak-fall-55h-x-45w/).

Both the swamp white oak and red oak are featured as street tree species in the Northeastern U.S., where urban foresters continue to diversify their community tree assemblages to withstand the pressures of the built landscape, invasive pests and pathogens, and a changing climate.

Summary

"We let the dead veteran season for a year in the sun it could no longer use, and then on a crisp winter's day we laid a newly filed saw to its bastioned base. Fragrant little chips of history spewed from the saw cut and accumulated on the snow before each kneeling sawyer. We sensed that these two piles of sawdust were something more than wood: that they were the integrated transect of a century; that our saw was biting its way, stroke by stroke, decade by decade, into the chronology of a lifetime, written in concentric annual rings of good oak." (Leopold 1949)

Summarized in Leopold's tale of the "good oak" in *A Sand County Almanac* (1949), it is evident that oak trees have longstanding, well-developed associations across the landscapes that they dominate. A formidable backbone to crucial structures throughout human history, an essential food source for both people and wildlife, and a contender for a top spot in the race of preferred urban trees, the oak is as significant as it is timeless.

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CHAPTER 2

NURSERY PRODUCTION METHODS AFFECT STREET TREE GROWTH

Introduction

With the advent of urban forestry and increased prominence of landscape trees, nurseries have risen to meet demands of municipalities and homeowners alike looking to green communities while reaping the benefits associated with urban trees (Ag Marketing Resource Center 2018). Production of landscape or street trees varies by nursery but can be categorized into two broad groups, container or field grown (Allen et al. 2017). Transplant processes, whereby trees are removed from the nursery system and planted elsewhere, differ among production methods, with various implications for costs associated with planting (Green et al. 2015), as well as effects on tree survivability and establishment (Allen et al. 2017). In the urban environment, costs and post-transplant success are further complicated by amplified stressors, namely water and nutrient stress and soil compaction (Nowak et al. 1990).

The container grown (CG) methods discussed in this study include pot-in-pot (PIP) and in-ground fabric (IGF) containers. These systems are common in the nursery industry, largely due to ease of handling (Allen et al. 2017), which reduces labor costs (i.e., equipment and time) associated with transplant (Green et al. 2015). A major drawback of CG systems is the risk for root circling and related root deformities (Appleton 1993; Appleton 1995; Gilman et al. 2010; Ortega et al. 2006), which may have implications for long-term growth and survivability (Neal and Lass 2014). IGF methods help to mitigate the effects of traditional plastic containers used for classic CG stock and are becoming more common for growing trees in the Northeast (Amherst Nurseries 2019). Known colloquially as grow bags, IGF containers are more flexible and reduce the amount of root circling observed in most CG stock (Allen et al. 2017). In contrast to field-grown methods, CG nursery stock typically have greater fine root biomass (Amoroso et al. 2010) and are less susceptible to damage from mechanical injury (Mathers et al. 2007).

The field grown method in this study refers to nursery stock grown in the ground that is balled and burlapped (B&B) upon excavation. B&B methods are historically the most popular nursery production method and thus, there is greater and more diverse stock available for purchase (Harris and Bassuk 1993; VanOteghem 2015). Compared to CG stock, B&B trees are often larger, but root ball excavation typically results in significant loss of total root mass (Amherst Nurseries 2019; Mathers et al. 2007), upwards of 95% in select instances (Harris and Bassuk 1993). Such severe reduction in root mass is likely to cause transplant shock, whereby trees are unable to absorb necessary water and nutrients, and essential carbon energy stores are lost (Allen et al. 2017; Struve 2009). Field grown trees do not experience the confined growing conditions associated with CG methods, resulting in improved root architecture (i.e., less circling and deformation), yielding increased rates of establishment, when root mass is maintained, and improved long-term survivability (Allen et al. 2017; Neal and Lass 2014).

Given these differences, this study seeks to address to what extent nursery production methods affect two species of oak planted as street trees in a suburban environment. Much of the research on this topic monitors tree conditions post-production but not post-transplant (Neal and Lass 2014). This information is important to urban forestry professionals, who are tasked with selecting tree species for their communities. If detected, differences in street tree performance due to effects of nursery production methods would also matter, especially since these methods influence costs associated with purchasing and planting. We hypothesize that PIP trees will exhibit slower rates of establishment than B&B trees, measured by growth in diameter and height following transplant. We further anticipate that IGF trees will outperform both PIP and B&B trees, as IGF containers should yield intermediate results between the restrictive nature of PIP methods and the excavation drawbacks associated with field grown nursery stock.

Methods

Study system and field data

In 2014, 48 oak trees were planted along suburban roads of South Amherst, Massachusetts. Comprised of two common street tree species, there were originally 24 swamp white oaks (*Quercus bicolor*) and 24 northern red oaks (*Quercus rubra*). These trees were produced from four different nursery systems and planted according to the methods described in Green et al. (2015), with additional details regarding specifications at time of planting provided by Yin et al. (2017). The nursery production methods discussed here include three of the four implemented in that study: balled and burlapped (B&B), container grown (CG) (PIP in Green et al. 2015 and above), and in-ground fabric (IGF). Bare root (BR) trees were discarded from analyses due to unnaturally high mortality rates that may be attributed to improper handling during transplant.

Measurements from the field were collected each spring (May), summer (July), and fall (September/October) from 2014 to 2018. Two to three crew members worked on the ground to record a suite of common growth metrics in English units (Table 1), ensuring each round of seasonal data collection occurred within one week, from start to finish, for all live trees.

Table 1. Descriptions of tree measurements used to monitor street tree growth in South Amherst, Massachusetts. All units measured to tenths of inches/feet.

Measurement	Description
Caliper at six inches (in.)	Diameter (i.e., caliper) 6 in. above root collar
DBH (in.)	Diameter at breast height (DBH) (i.e., 4.5 ft from ground)
Tree height (ft)	Total tree height; distance from ground to live top
Height of first branch (ft)	Distance from ground to first live branch
Crown length (ft)	Difference between tree height and height of first branch
Crown width (NS) (ft)	Distance between live branches measured North to South
Crown width (EW) (ft)	Distance between live branches measured East to West
Sun shoots (ft)	Length of seasonal growth for five sun shoots*

*Defined as branches growing towards the top of tree crown, receiving maximal sunlight

Study Site

The town of Amherst (44.3861° N, -72.5374° W) is situated in Hampshire County, 144 ft elevation, where average highest summer temperatures approximate 82 °F, and average coldest winter temperatures hover around 33 °F. Local rainfall approaches 46 in. each year, with 36 in. of annual snowfall (U.S. Climate Data 2019). The study site in South Amherst (Figure 8) is considered suburban and has a local population of 4,994 (U.S. Census Bureau 2010). The area is subject to through traffic, especially due to the nearby University of Massachusetts Amherst, and trees planted along these roadways are exposed to conditions that reflect those of their more urban street tree counterparts, such as salt deposition following winter weather events and increased exposure to mortality from car impacts.

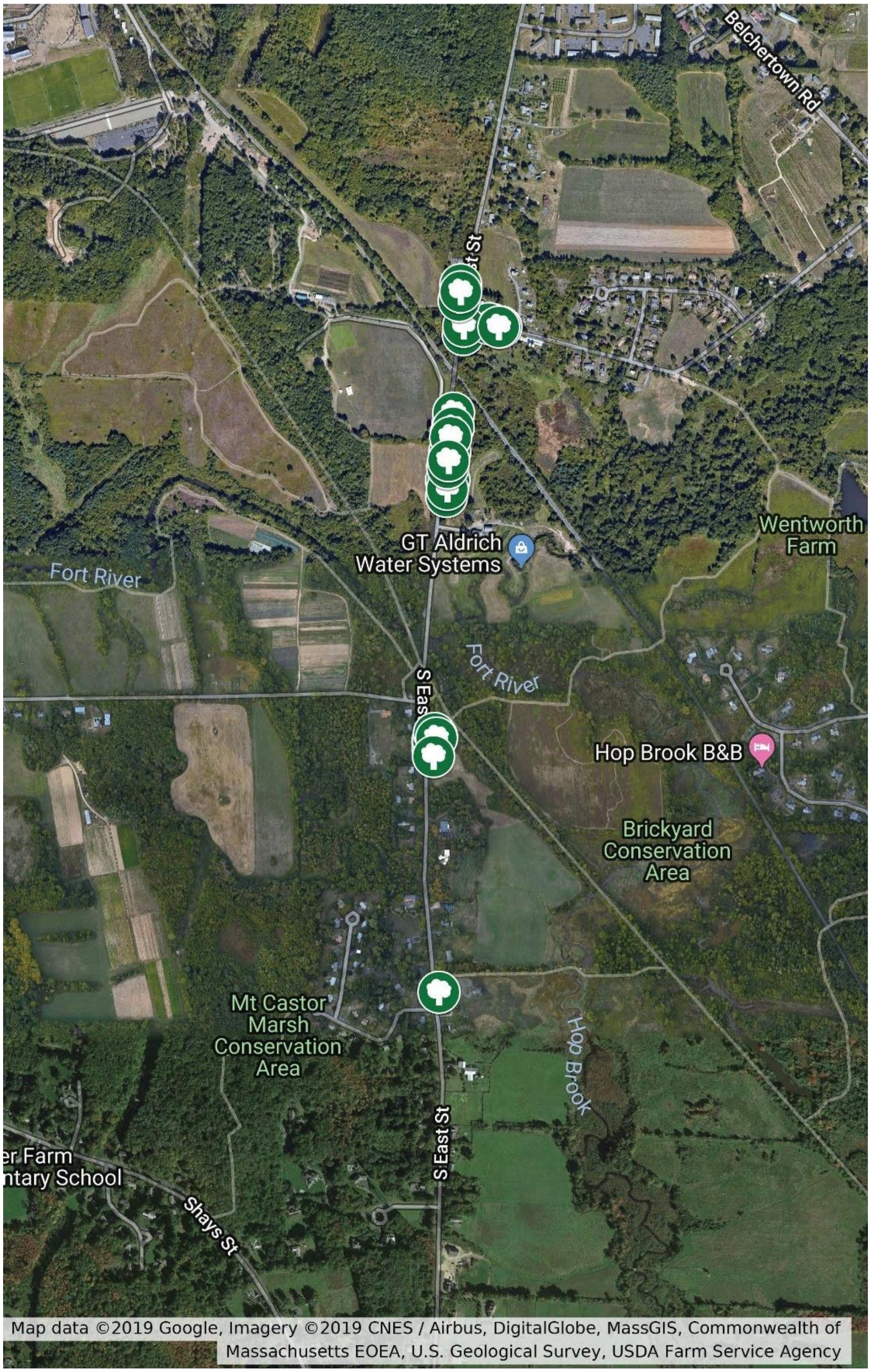


Figure 8. Study site in South Amherst, Massachusetts, with green and white icons depicting a system of street trees monitored and measured each spring, summer, and fall from 2014 to 2018.

Data processing and analyses

Data processing occurred in Excel, where fall measurements for each year were isolated from the full dataset. Fall measurements capture the growth that occurred during the most recent growing season, from spring to fall of that year. By isolating fall measurements, we can monitor growth each year and account for differences in yearly growth, along with other factors. In addition to BR trees, five dead trees and three trees with missing data were also removed from the dataset, resulting in a total of 32 trees for analyses (Table 2).

Measurements of greatest interest for monitoring tree growth include caliper at six inches (caliper), diameter at breast height (DBH), and total tree height (height). Caliper is used in the nursery industry as a standard to describe tree size (AmericanHort 2004), while DBH and height are common inventory metrics (Bechtold 2003). Remaining data were excluded from the set of analyses pertaining to tree growth in this study. Given yearly fall data, we can calculate the change in measurements from one growing season (i.e., year) to the next, or "delta" (Δ, change in) caliper/DBH/height. These Δ values were calculated in Excel and added as data columns beginning in 2015 (i.e., Δ values from Fall 2014 to Fall 2015 are considered 2015 growth, or Δ caliper/DBH/height from 2014 to 2015). The statistical analyses in this study implement Δ values, rather than yearly fall measurements, to detect whether factors influence yearly growth.

The remainder of data processing and all analyses were conducted in R version 3.4.3 (R Core Team 2017), as well as figure creation. Rmisc was employed in data processing and calculating confidence intervals (Hope 2013). Analyses implemented the car package (Fox and Weisberg 2011), while ggplot2 (Wickham 2009) and ggpubr

(Kassambara 2018) were used to create figures. The lm function fit linear models with normal error distributions to Δ caliper, DBH, and height data to identify whether year, species, and/or nursery production method explained differences in growth among trees. Model residuals did not grossly deviate from assumptions of normality.

Table 2. Number of street trees in South Amherst, MA measured each fall from 2014 to 2018. Trees are grouped by species, *Quercus bicolor* and *Quercus rubra*, and nursery production method, balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF).

	B&B	**CG**	**IGF**	**Row total**
Q. bicolor	7	8	5	20
Q. rubra	6	0	6	12
Column total	13	8	11	32

Results

Mortality/Survivability

Survivability is frequently discussed in the literature regarding effects of nursery production methods on transplant success. After discarding BR trees from analyses due to unnaturally high levels of mortality, there were four trees that died during the first two years following planting (i.e., 2014 and 2015). An additional tree was killed from car impact in 2018. Of the four trees that did not survive, two were *Q. rubra* B&B trees and two were *Q. bicolor* IGF trees. As such, sample sizes were too small among production methods for statistical analysis.

Total change in growth (Fall 2014 to Fall 2018)

The raw data indicate that *Q. bicolor* trees grew more than *Q. rubra* trees from Fall 2014 to Fall 2018 in all three metrics, caliper (Figure 9A), DBH (Figure 9C), and height

(Figure 9E). IGF trees grew more than B&B and CG trees in caliper and height (Figure 9B and Figure 9F, respectively) but not DBH (Figure 9D). There were mixed responses between B&B and CG trees; B&B trees showed greater caliper growth over CG trees, but CG trees exhibited greater changes in DBH and height over B&B trees. For the metrics by which CG appear to be growing larger than B&B, it must be noted that there were no CG *Q. rubra* trees (Table 2). Significant differences between species are likely to be driving mixed responses to methods in these instances (Figure 9).

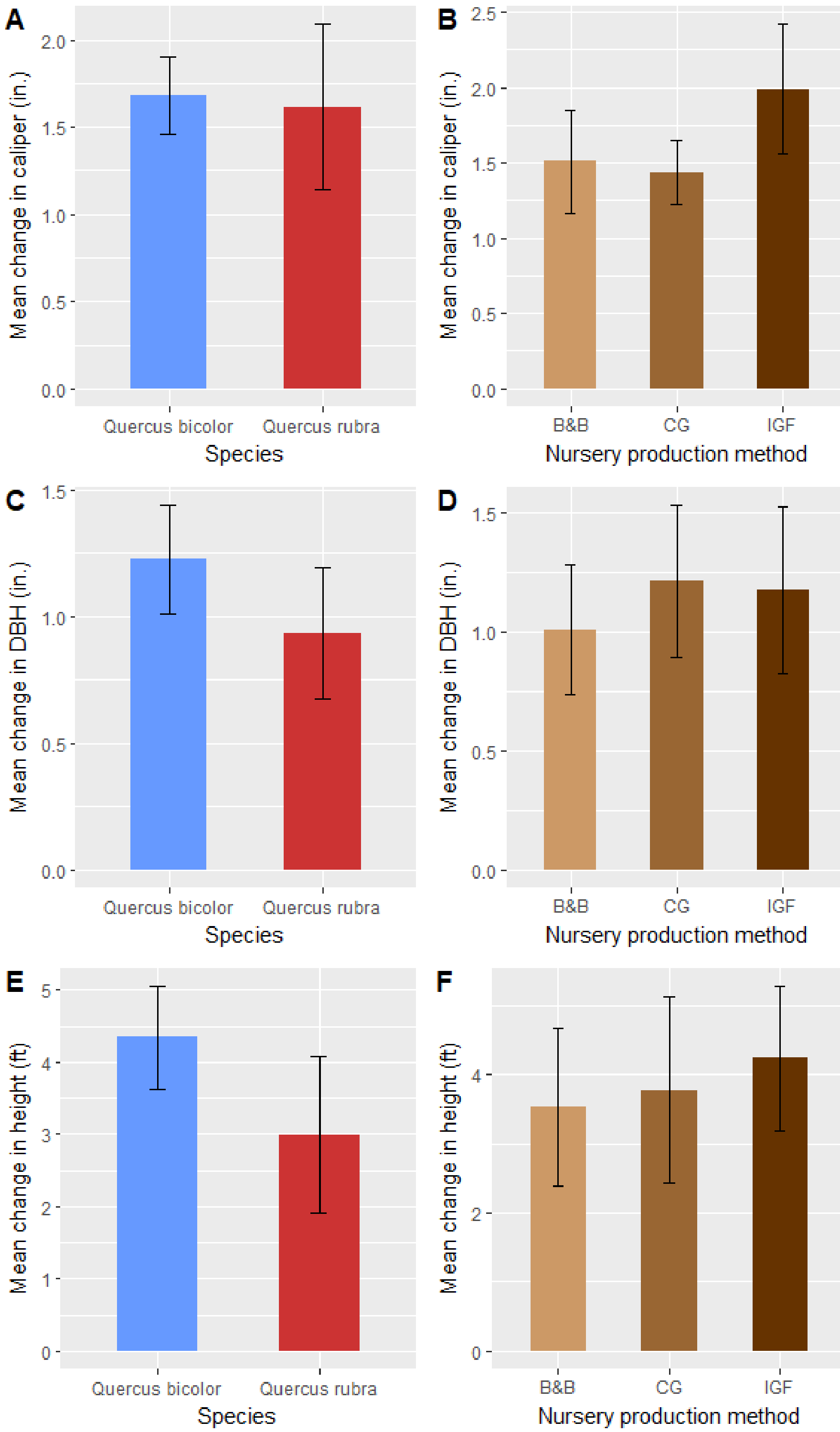
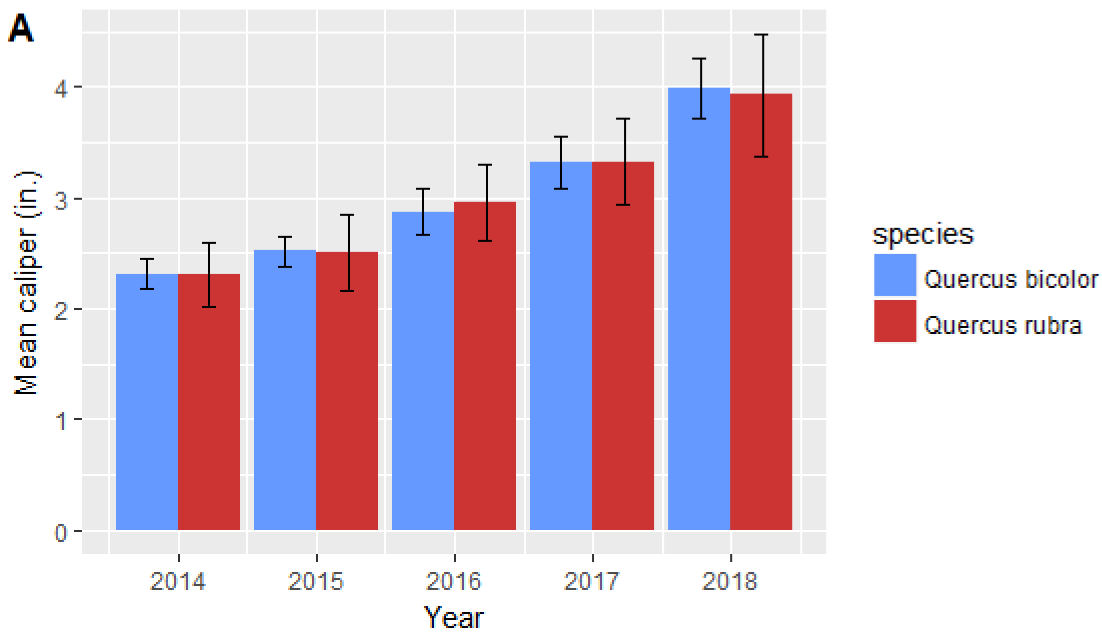


Figure 9. Mean change in caliper at six inches (caliper), diameter at breast height (DBH), and total tree height (height) of two tree species produced from three different nursery production methods, balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), from Fall 2014 to Fall 2018. Error bars represent 95% confidence intervals. (N=32)

Yearly growth

The raw data indicate similar caliper measurements for both *Q. bicolor* and *Q. rubra* trees from Fall 2014 through Fall 2018 (Figure 10A). IGF trees grew more than B&B trees, and CG trees were consistently smallest in caliper size (Figure 10B). Greater differences between *Q. bicolor* and *Q. rubra* trees were observed in DBH measurements, with *Q. bicolor* trees consistently growing more than *Q. rubra* trees, according to this metric (Figure 11A). B&B trees exhibited greater DBH than both CG and IGF trees from 2014 through 2017, but CG and IGF trees approximate B&B trees in DBH measurements by 2018 (Figure 11B). According to height data, *Q. rubra* trees were consistently taller than *Q. bicolor* trees, though *Q. bicolor* trees appear to have experienced greater growth in height from 2014 to 2018 (Figure 12A). B&B and IGF trees were similar in height and both taller than CG trees (Figure 12B).



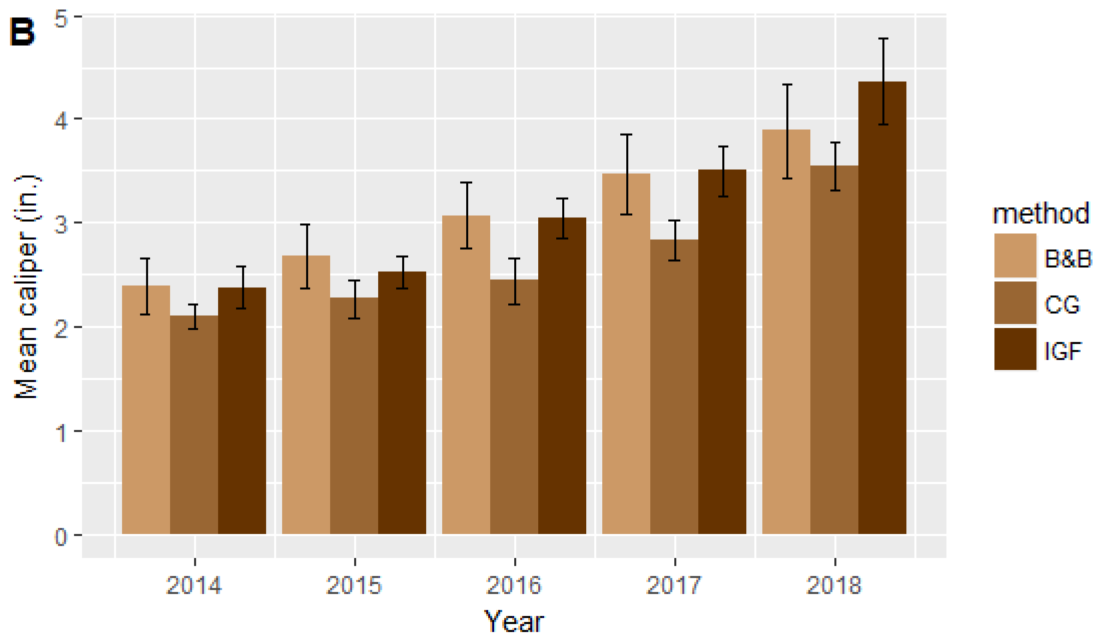


Figure 10. Mean caliper at six inches (caliper) of two tree species (A) produced from three different nursery production methods (B), balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), each fall from 2014 to 2018. Error bars represent 95% confidence intervals. (N=160, n=32)

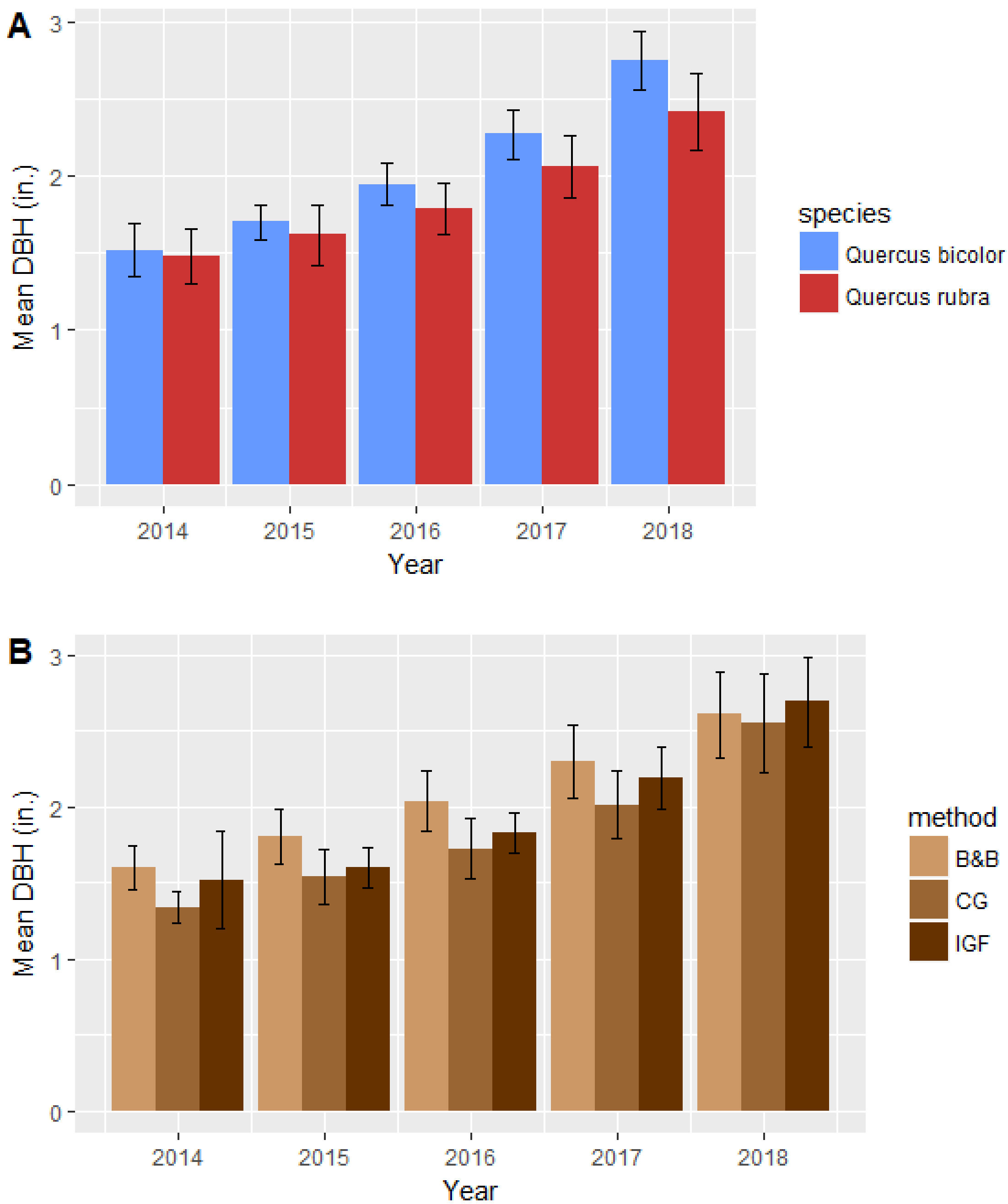


Figure 11. Mean diameter at breast height (DBH) of two tree species (A) produced from three different nursery production methods (B), balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), each fall from 2014 to 2018. Error bars represent 95% confidence intervals. (N=160, n=32)

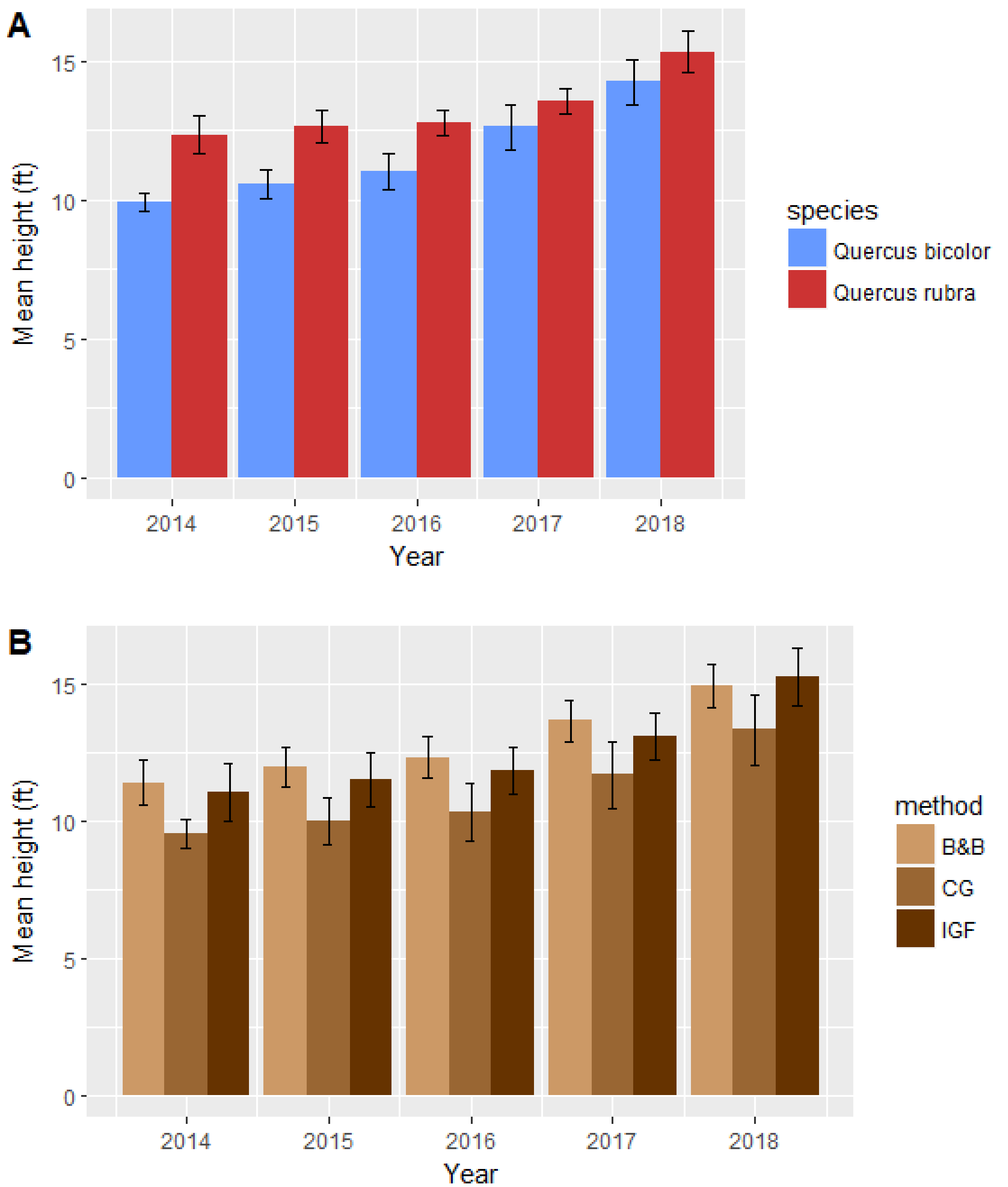


Figure 12. Mean total height (height) of two tree species (A) produced from three different nursery production methods (B), balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), each fall from 2014 to 2018. Error bars represent 95% confidence intervals. (N=160, n=32)

Year, species, and method effects

A linear regression model with additive effects of year, species, and method was used to estimate growth, or Δ caliper/DBH/height:

$$Growth_{it} = \beta_0 + \beta_1 Y16_t + \beta_2 Y17_t + \beta_3 Y18_t + \beta_4 QR_{it} + \beta_5 CG_{it} + \beta_6 IGF_{it} + u_{it},$$

where β_0 represents growth for *Q. bicolor* B&B trees in year 2015. This model allows us to estimate yearly growth, while holding effects of species and method constant. We can also test for parameter equality to determine whether CG (β_5) and IGF (β_6) methods have equal effects (Williams 2015, "linear hypothesis test" in R 3.4.3 package car) as follows:

$$H_0: \beta_5 = \beta_6$$

$$H_A: \beta_5 \neq \beta_6.$$

According to the linear regression model explaining Δ caliper, *Q. rubra* trees exhibited less caliper growth than *Q. bicolor* trees (but not significantly, $p = 0.17$), CG trees exhibited less growth than B&B trees (but not significantly, $p = 0.40$), and IGF trees exhibited significantly greater caliper growth than B&B trees ($p < 0.01$) (Table 3). A test for equality of parameter estimates determined that IGF trees also exhibited significantly greater caliper growth than CG trees ($p < 0.01$).

Table 3. Coefficient estimates from a linear model with a normal error distribution explaining growth in caliper at 6 inches (caliper) for street trees planted in South Amherst, Massachusetts.

Coefficient	**Estimate**	**Standard error**	**t-value**	**Pr(>|t|)**
Intercept	0.19993	0.05321	3.757	0.000266***
2016	0.18125	0.05856	3.095	0.002445**
2017	0.21250	0.05856	3.629	0.000419***
2018	0.43750	0.05856	7.471	1.37e-11***
Q. rubra	-0.06678	0.04798	-1.392	0.166535
CG	-0.04837	0.05710	-0.847	0.398595
IGF	0.12641	0.04815	2.625	0.009776**

† significant at p < 0.10; * significant at p < 0.05; ** significant at p < 0.01; *** significant at p < 0.001

Fitting the same regression to Δ DBH data, we observe again that *Q. rubra* trees grew less than *Q. bicolor* trees (approaching significance, p = 0.05). CG grew slightly more than B&B trees (but not significantly, p = 0.76), as did IGF trees (p = 0.24) (Table 4). A test of parameter equality determined that IGF trees did not exhibit significantly greater growth in DBH than CG trees (p = 0.52).

Table 4. Coefficient estimates from a linear model with a normal error distribution explaining growth in diameter at breast height (DBH) for street trees planted in South Amherst, Massachusetts.

Coefficient	**Estimate**	**Standard error**	**t-value**	**Pr(>|t|)**
Intercept	0.17197	0.04490	3.830	0.000205***
2016	0.05625	0.04942	1.138	0.257261
2017	0.14062	0.04942	2.846	0.005207**
2018	0.26875	0.04942	5.438	2.83e-07***
Q. rubra	-0.07899	0.04049	-1.951	0.053391†
CG	0.01474	0.04818	0.306	0.760124
IGF	0.04789	0.04063	1.179	0.240890

† significant at p < 0.10; * significant at p < 0.05; ** significant at p < 0.01; *** significant at p < 0.001

Modeling Δ height data, we observe that *Q. rubra* trees exhibited significantly less growth in height compared to *Q. bicolor* trees ($p < 0.01$). CG trees grew less than B&B trees (but not significantly, $p = 0.37$), while IGF trees grew more than B&B trees (but not significantly, $p = 0.12$) (Table 5). A test of parameter equality determined that IGF trees exhibited significantly greater growth in height than CG trees ($p = 0.04$).

Table 5. Coefficient estimates from a linear model with a normal error distribution explaining growth in total tree height (height) for street trees planted in South Amherst, Massachusetts.

Coefficient	**Estimate**	**Standard error**	**t-value**	**Pr(>|t|)**
Intercept	0.6407	0.1502	4.265	3.00e-05***
2016	-0.1625	0.1653	-0.983	0.32767
2017	0.7875	0.1653	4.763	5.35e-06***
2018	0.1719	0.1653	7.087	9.87e-11***
Q. rubra	-0.4491	0.1355	-3.315	0.00121**
CG	-0.1462	0.1612	-0.907	0.36624
IGF	0.2141	0.1360	1.575	0.11793

† significant at $p < 0.10$; * significant at $p < 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.001$

Effects of 2016 drought and 2018 wet season

Massachusetts experienced significant drought conditions in 2016, two years after tree planting. The 2016 drought lasted 48 weeks, extending into May of the following year, earning the record for longest drought duration since 2000 (National Integrated Drought Information System 2019). In contrast, year 2018 saw record highs for rainfall, as the wettest year on record for the state, with nearly 61 in. of rain (Swasey 2019). To account for effects of 2016 drought conditions, interaction terms between year 2016 and species and between year 2016 and nursery production methods were added to the linear model:

$$Growth_{it} = \beta_0 + \beta_1 Y16_t + \beta_2 Y17_t + \beta_3 Y18_t + \beta_4 QR_{it} + \beta_5 CG_{it} + \beta_6 IGF_{it} + \beta_7(Y16_t * QR_{it}) + \beta_8(Y16_t * CG_{it}) + \beta_9(Y16_t * IGF_{it}) + u_{it}.$$

Model summaries indicated that drought conditions significantly decreased caliper growth for CG trees in 2016 ($p = 0.05$), while no other significant effects were observed for Δ caliper, DBH, or height.

Discussion

The results from this study suggest that both species and nursery production method affect street tree establishment and growth post-transplant. *Q. bicolor* trees appear to respond more favorably to transplant than *Q. rubra* trees, which aligns with the literature (Backstrup and Bassuk 2000; Watson and Himelick 2013) and information provided by experts in the landscape tree industry (Casey Trees 2013; The Morton Arboretum 2019). As hypothesized, IGF trees generally appeared to grow more than B&B and CG trees. Differences between B&B and CG trees varied depending upon metric, with CG trees exhibiting less growth in caliper and height but not DBH, according to the linear models accounting for yearly effects. These results may be inconsistent for two potential reasons: (1) lack of *Q. rubra* CG trees in the dataset and/or (2) artificial inflation of DBH caused by inconsistencies where DBH was measured, either due to human error or adjustments above/below lateral branches.

Though statistical analyses were not possible with mortality data, it is worth noting that no CG trees were lost to post-transplant mortality. It is also interesting that, of the four trees that died, species and method aligned; both *Q. rubra* trees were B&B stock, while both *Q. bicolor* trees were IGF stock. Post-transplant failure for *Q. rubra* B&B

trees is not surprising, given the potential for significant loss of root mass in B&B stock (Koeser et al. 2009) and transplant difficulties associated with *Q. rubra* trees (Harris et al. 2002; Watson and Himelick 2013). Loss of *Q. bicolor* IGF trees is puzzling, since *Q. bicolor* trees typically respond better to transplant (Curtis 2010), and IGF trees were expected to better tolerate transplant shock, compared to other methods. Site may have influenced the survivability of these trees, as the two *Q. rubra* B&B trees were planted near each other in one location, while the two *Q. bicolor* IGF trees were planted near each other at another location.

One major caveat of this study is that site was not considered a factor for analyses. As mentioned above, site may have influenced post-transplant success and perhaps even growth. Planting sites were confined to public rights-of-way along a few streets determined by the town of Amherst, and site selection was largely governed by species suitability, with *Q. bicolor* trees planted in wetter sites than *Q. rubra* trees. In this way, site was accounted for in study design, to some extent. Another caveat, as previously mentioned, was the lack of *Q. rubra* CG trees in the dataset. While a detailed study design would have ensured replicates of each nursery production method for both species, this was impractical given the constraints of this system. Trees were acquired from local partners in Massachusetts and New Hampshire, as described by Green et al. (2015), and were free of purchasing costs. The trees planted in this system were consequently based on availability from donating partners.

Considering these caveats, the data still suggest that species, nursery production method, and perhaps an interaction between the two may contribute to the ability of street trees to establish and grow in the urban landscape. These results are important to urban forestry practitioners, such as community foresters, tree wardens, and certified arborists, as well as landscape professionals, making purchasing and planting decisions in the Northeast. In a previous study of this system by Green et al. (2015), IGF trees were, on average, less expensive to plant ($5.38) than both B&B and CG trees ($11.01 and $6.52, respectively). If roots can be conserved during field excavation, IGF trees may be preferred over CG nursery stock and other field grown methods due to reduced costs and improved post-transplant growth. CG trees could have an advantage over field grown stock, especially more expensive B&B trees, when considered in combination with increased odds for establishment following transplant, though CG trees at larger caliper sizes are not as readily available (Harris and Bassuk 1993; VanOteghem 2015). As recommended in the world of urban forestry, planting decisions should be based on the "right tree, right place" principle, whereby species, site conditions, and other relevant factors are considered.

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CHAPTER 3

THE BREAKEVEN POINT: A COST-BENEFIT ANALYSIS FOR STREET TREE PLANTING

Introduction

Ecosystem services provided by the urban forest, particularly those estimated in U.S. dollars, are well-represented and increasing in the literature (Austin 2014; Benedict and McMahon 2006; Gómez-Baggethun et al. 2013; McPherson et al. 2011; Roy et al. 2012). This is particularly relevant for professionals in the field of urban forestry and related practitioners, who are working to green communities with limited budgets and continue to advocate for trees in the built environment. Services provided by street trees span cultural and social functions (Austin 2014; Tyrväinen et al. 2005; Zhou and Rana 2012), which can be difficult to quantify, along with more tangible effects like carbon storage and sequestration, stormwater mitigation, pollution removal, energy savings, noise reduction, and increased property values (Bolund and Hunhammar 1999; Escobedo et al. 2011; Livesley et al. 2016; McPherson et al. 2007; Nowak and Dwyer 2007).

The development of tools such as i-Tree (https://www.itreetools.org/) by the U.S. Forest Service have enabled estimating the monetary valuation of specific urban forest benefits, namely those related to carbon emissions, stormwater runoff, and pollution. As the flagship tool, i-Tree Eco v6.0 is currently the most comprehensive application of the software suite (i-Tree 2019a). Using site and species information coupled with tree measurements and field data, it models both compensatory values and ecosystem services provided by trees and estimates their economic value; the application can also be used to forecast future benefits (Figure 13).

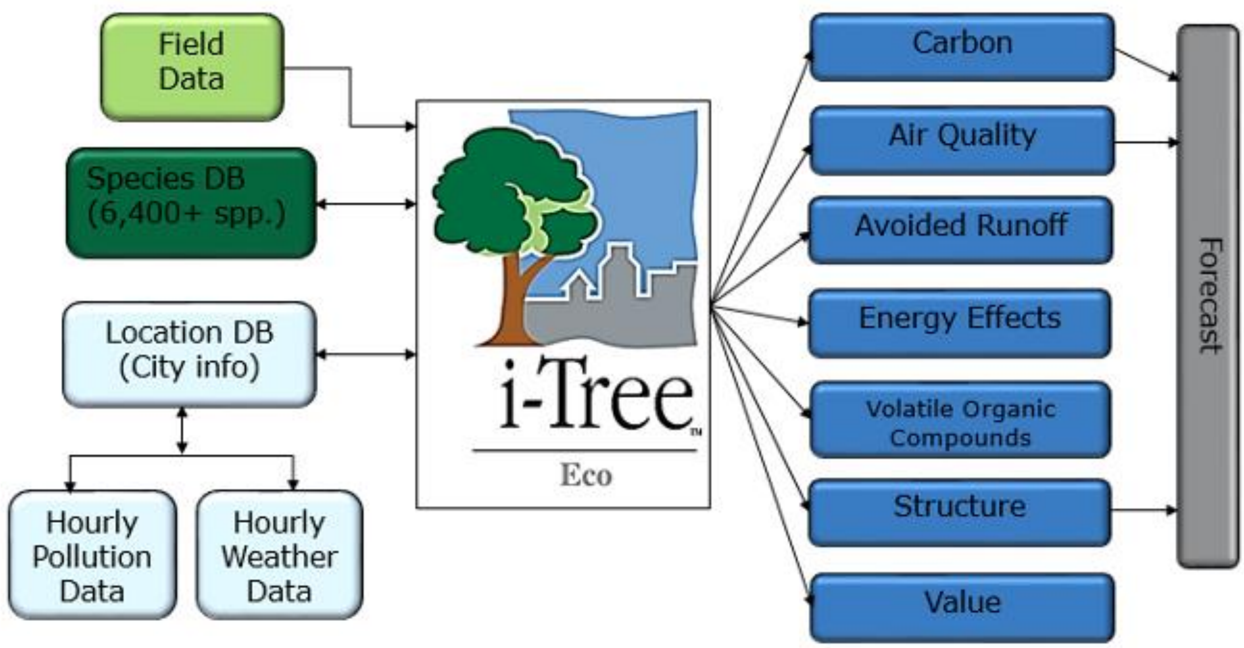

Figure 13. Schematic of i-Tree Eco inputs and outputs for modeling ecosystem services.

The i-Tree Eco v6.0 User's Manual (i-Tree 2019b) offers directions for new inventory projects; it provides information about how to structure study design, data collection protocols, and instructions for navigating the i-Tree interface, as well as interpretation of model and forecast outputs. Both the application and the manual help the user to select variables and specify parameters, while providing definitions of ecosystem services (Table 6, with benefits and valuations specifically related to the model outputs of this study) and the information used to calculate them (Figure 14).

Table 6. Definitions and values implemented for calculating benefits from ecosystem services provided by trees using i-Tree Eco v6.0 by the U.S. Forest Service. Definitions were taken from the i-Tree Eco v6.0 User's Manual, and figures for valuation were provided with model outputs using the desktop application (iTree 2019b).

Benefit	Definition (D) and valuation (V)
Carbon storage	(D) A measure of the carbon that is stored within trees. This is the amount of carbon that is bound up in both the above-ground and below-ground parts of woody vegetation. (V) Carbon storage and gross carbon sequestration value is calculated based on the price of $0.06486 per pound.
Gross carbon sequestration	(D) A measure of the carbon sequestered by trees calculated as the difference in estimates of carbon storage between Year X and Year X +1, where carbon sequestration is a measure of the carbon (in the form of carbon dioxide) that is removed from the atmosphere by trees. (V) Carbon storage and gross carbon sequestration value is calculated based on the price of $0.06486 per pound.
Avoided runoff	(D) A measure of the stormwater runoff that is avoided because of rainfall interception by trees, which partially intercept precipitation on their leaves and other surfaces. Avoided runoff is estimated by comparing the hourly precipitation processes and total annual surface runoff volume modeled for the study area as it occurs with trees present and as it would occur if there were no trees. (V) Avoided runoff value is calculated by the price $0.067/ft^3. The user-designated weather station reported 37.3 inches of total annual precipitation.
Pollution removal	(D) A measure of the air pollution that is removed from the atmosphere by trees. Pollution removal is calculated for nitrogen dioxide (NO2), sulfur dioxide (SO2), ozone (O3), carbon monoxide (CO), and particulate matter less than 2.5 microns (PM2.5). Trees remove gaseous air pollution primarily by uptake via leaf stomata, though some gases are removed by the plant surface. Trees also remove pollution by intercepting airborne particles. Some particles can be absorbed into the tree, though most particles that are intercepted are retained on the plant surface. (V) Pollution removal value is calculated based on the prices of $0.69 per pound (CO), $0.50 per pound (O3), $0.07 per pound (NO2), $0.02 per pound (SO2), $12.73 per pound (PM2.5).
Structural value	(D) Structural value is the compensatory value calculated based on the local cost of having to replace a tree with a similar tree. (V) Not provided.

	DERIVED VARIABLES		ECOSYSTEM SERVICES										
DIRECT MEASURES	Leaf Area	Leaf Biomass	Carbon Storage	Gross Carbon Sequestration	Net Carbon Sequestration	Energy Effects	Air Pollution Removal	Avoided Runoff	Transpiration	VOC Emissions	Compensatory Value	Wildlife Suitability	UV Effects
Species	D	D	D	D	D	D	I	I	I	D	D		
Diameter at breast height (DBH)			D	D	D						D	D	
Total height	D	D	D	D	D	D	I	I	I	I		D	
Crown base height	D	D	C				I	I	I	I			
Crown width	D	D	C				I	I	I	I			
Crown light exposure (CLE)				D	D								
Percent crown missing	D	D	C			D	I	I	I	I			
Crown health (condition/dieback)				D	D						D	D	
Field land use			D	D	D						D	D	
Distance to building						D							
Direction to building						D							
Percent tree cover						D	D	D				D	D
Percent shrub cover												D	
Percent building cover						D							
Ground cover composition												D	
Maintained Grass, Unmaintained Grass, and Herbaceous % cover							I						

D Directly used I Indirectly used C Conditionally used

Figure 14. Variables influencing calculations of ecosystem services provided by trees using i-Tree Eco v6.0 by the U.S. Forest Service (i-Tree 2019a).

Research analyzing benefits modeled from i-Tree has often evaluated net benefits or benefit-cost ratios (Foster and Duinker 2017; Millward and Sabir 2011; Soares et al. 2011; Widney et al. 2016), though few, if any, have attempted to identify the breakeven point in a cost-benefit analysis. Using cost figures from previous work by Green et al. (2015), this study seeks to identify how many years it takes for benefits to surpass costs (i.e., the breakeven point) in a system of street trees planted in South Amherst, Massachusetts.

Methods

i-Tree project configuration

Before conducting i-Tree analyses, new projects must first be defined. Project definition includes location, population, and specification of years for weather/pollution data, as well as weather station information. Data collection options (i.e., fields) are also determined at this stage. The most important (and only) variables required by i-Tree are (1) species and (2) DBH; remaining measurements for this system were discarded so as not to misconstrue software projections of tree growth. Basic information regarding site, such as land use, tree status, and GPS coordinates, were selected for data collection, and nursery production method was defined as an additional field (Table 7).

Table 7. Data collection fields used for an analysis of street trees using i-Tree Eco v6.0.

Data field	**Description**
Species	*Q. bicolor* or *Q. rubra*
DBH	Diameter at breast height
Land Use	Residential
Status	Planted
Street tree or not	Street tree
GPS coordinates	Latitude, longitude
Public/private	Public
Nursery production method	B&B, CG, or IGF

Data processing and i-Tree output

The same 32 trees analyzed in Chapter 2 were used for this study. Fall 2018 DBH data and additional fields were imported to i-Tree via Excel and sent to the software's server for processing. An i-Tree report was generated containing summaries of individual tree benefits ("Individual Tree Benefits Summary"), which was downloaded as an Excel spreadsheet. To project DBH growth over the next 30 years, which captures the upper limit of mean street tree life expectancy (Roman and Scatena 2011), the “Forecast” report was selected for configuration. Basic options were set to defaults, while annual mortality and tree planting rates were specified. Since the establishment period for these trees is assumed to be complete by Fall 2018 (Sherman et al. 2016, Struve 1993), a mortality rate of 5% was implemented, reflecting average annual survival rates for street trees (Roman and Scatena 2011). Tree planting rates were customized to account for default options resulting in significant population decline, with two trees planted per year. For example, if this population of 32 trees experienced 5% annual mortality (without supplemental planting), all trees would be eliminated by year 20. Though these are street trees, they are anticipated to perform better than their more urban counterparts. Incorporating tree planting at a low rate buffers from unnaturally high mortality at the population level, while still capturing expected survival rates (and thus, mortality) for this system.

Using average annual DBH growth rates forecasted from i-Tree, yearly DBH measurements for each tree were calculated in Excel, starting in 2018. Data from every five years for 30 years was submitted to i-Tree for individual tree benefits in years 2023, 2028, 2033, 2038, 2043, and 2048. All other data fields were kept constant. The DBH data taken Fall 2014 were also submitted to capture benefits at timestep 0. Individual tree benefits were compiled in one Excel spreadsheet, while total benefits summed across all 32 trees in 2014, 2018, and each subsequent five-year interval were compiled as a separate dataset in Excel.

Cost-benefit analyses

To examine differences in street tree benefits based on nursery production method and determine a breakeven point for this study system, both individual tree benefits and total benefits were analyzed in R version 3.4.3 (R Core Team 2017). Average benefits provided by trees from each nursery production method were calculated for years 2014, 2018, and subsequent five-year intervals. Total benefits provided by all 32 trees in those same years were used to model annual benefits from 2014 to 2048, whereby 2014 is considered timestep 0, and 2048 is timestep 34 (Table 8). A linear model with a normal error distribution (refer to Chapter 2) was fit to the data, and regression coefficients were used to estimate annual benefits for each timestep and interim years.

Table 8. Calendar year and corresponding timestep used in a linear model explaining benefits provided by street trees over approximately a 30-year period.

Year	Timestep
2014	0
2018	4
2023	9
2028	14
2033	19
2038	24
2043	29
2048	34

In addition to annual total benefits, costs to purchase and plant each tree according to nursery production method were used to calculate net present value (NPV, total future benefits minus costs discounted to the present) (McPherson 2011). A discount rate of 5% was used for NPV calculations in Excel. Most NPV calculations in traditional and urban forestry sectors implement discount rates between 0–10% (Peterson and Straka 2012; McPherson 2011; Peper et al. 2009; Row et al. 1981; WDNR 2016). Costs were considered one-time expenses to purchase and plant trees at timestep 0 (i.e., 2014). Average prices for swamp white oak (*Quercus bicolor*) and northern red oak (*Q. rubra*) B&B, CG, and IGF trees at 2 in. caliper were provided by Amherst Nurseries (Amherst Nurseries 2018; J. Kinchla, Amherst Nurseries, personal communication, 2019), a local partner that originally provided the nursery stock. Costs to plant according to nursery production method were again based on results from Green et al. (2015). Total costs for all trees at timestep 0 was $7124.47 (Table 9).

Table 9. Total costs by nursery production methods, balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), for a system of street trees planted in South Amherst, MA in Spring 2014. Purchase prices were attained from a local nursery, and costs to plant were based on a study of this same system by Green et al. (2015).

	No. trees	**Cost to purchase**	**Cost to plant**	**Total**
B&B	13	225	11.01	3068.13
CG	8	225	6.52	1852.16
IGF	11	195	5.38	2204.18

NPV at each timestep (from 0 to 34, or 2014 to 2048) was calculated in Excel and plotted in R using the package ggplot2 (Kassambara 2018). A smoothed loess curve was added to the plot, and the breakeven point, where the fit curve intersects a horizontal line representing the shift from negative to positive cash flow (NPV = $0.00), was estimated (Gallo 2014). The Rmisc package (Hope 2013) was used for processing tree benefit data and calculating confidence intervals.

Results

Yearly benefits

In 2014, mean benefits provided by a tree were worth almost $50. Benefits surpassed costs per tree (to purchase and plant) by 2023, with the average tree generating just over $260 (Figure 15).

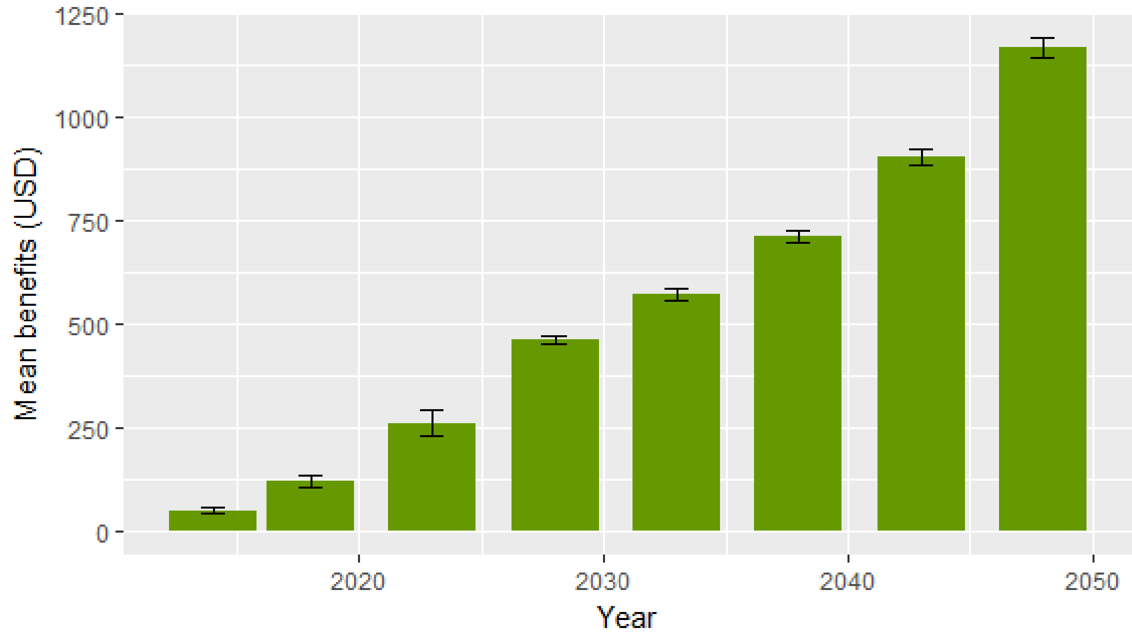

Figure 15. Average benefits per tree, in U.S. dollars, provided by street trees in South Amherst, MA in years 2014, 2018, 2023, 2038, 2043, and 2048 based on i-Tree Eco v6.0 estimates of ecosystem services.

Trees gained most of their benefits from structural value, followed by carbon storage, and finally, annual benefits from remaining ecosystem services, gross carbon sequestration, avoided runoff, and pollution removal (Figure 16).

						Annual benefits									
Tree ID	Species Name	DBH	Structural Value	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Carbon Avoided		Pollution Removal		Energy Savings	Total Annual Benefits
		(in)	($)	(lb)	($)	(lb/yr)	($/yr)	(ft^3/yr)	($/yr)	(lb/yr)	($/yr)	(oz/yr)	($/yr)	($/yr)	($/yr)
701	Swamp white oak	4.50	430.91	52.40	3.40	4.60	0.30	3.70	0.25	N/A	N/A	1.40	0.06	N/A	0.60
703	Swamp white oak	4.20	414.72	44.10	2.86	4.10	0.27	3.40	0.23	N/A	N/A	1.30	0.05	N/A	0.55
704	Swamp white oak	4.10	409.57	41.50	2.69	4.00	0.26	3.30	0.22	N/A	N/A	1.30	0.05	N/A	0.53
705	Swamp white oak	3.20	174.10	22.30	1.45	2.80	0.18	2.40	0.16	N/A	N/A	0.90	0.04	N/A	0.38
706	Swamp white oak	4.00	272.03	39.00	2.53	3.80	0.25	3.20	0.21	N/A	N/A	1.20	0.05	N/A	0.51
707	Swamp white oak	4.60	436.56	55.30	3.59	4.70	0.31	3.90	0.26	N/A	N/A	1.50	0.06	N/A	0.62
708	Swamp white oak	4.00	272.03	39.00	2.53	3.80	0.25	3.20	0.21	N/A	N/A	1.20	0.05	N/A	0.51
711	Swamp white oak	3.60	220.34	30.00	1.94	3.30	0.21	2.80	0.18	N/A	N/A	1.10	0.04	N/A	0.44
713	Swamp white oak	4.00	272.03	39.00	2.53	3.80	0.25	3.20	0.21	N/A	N/A	1.20	0.05	N/A	0.51
714	Swamp white oak	3.70	232.75	32.10	2.08	3.40	0.22	2.90	0.19	N/A	N/A	1.10	0.04	N/A	0.46
715	Swamp white oak	4.10	409.57	41.50	2.69	4.00	0.26	3.30	0.22	N/A	N/A	1.30	0.05	N/A	0.53
716	Swamp white oak	3.80	245.50	34.30	2.22	3.60	0.23	3.00	0.20	N/A	N/A	1.10	0.05	N/A	0.47
717	Swamp white oak	3.90	258.59	36.60	2.37	3.70	0.24	3.10	0.21	N/A	N/A	1.20	0.05	N/A	0.49
718	Swamp white oak	3.80	245.50	34.30	2.22	3.60	0.23	3.00	0.20	N/A	N/A	1.10	0.05	N/A	0.47
719	Swamp white oak	3.10	163.39	20.60	1.34	2.60	0.17	2.30	0.15	N/A	N/A	0.90	0.04	N/A	0.36
720	Swamp white oak	3.30	185.15	24.10	1.56	2.90	0.19	2.50	0.17	N/A	N/A	1.00	0.04	N/A	0.39
721	Swamp white oak	3.50	208.27	27.90	1.81	3.10	0.20	2.70	0.18	N/A	N/A	1.00	0.04	N/A	0.42
723	Swamp white oak	4.30	419.99	46.70	3.03	4.30	0.28	3.50	0.24	N/A	N/A	1.40	0.05	N/A	0.57
724	Swamp white oak	3.50	208.27	27.90	1.81	3.10	0.20	2.70	0.18	N/A	N/A	1.00	0.04	N/A	0.42
725	Swamp white oak	3.70	232.75	32.10	2.08	3.40	0.22	2.90	0.19	N/A	N/A	1.10	0.04	N/A	0.46

Figure 16. Part of the 2023 “Individual Tree Benefits Summary” from i-Tree Eco v6.0, modeling ecosystem services provided by a system of street trees in South Amherst, MA.

Reflecting results from Chapter 2, effects of species and nursery production method were significant in predicting average total benefits using a linear additive model with a normal error distribution that accounted for year, species, and method. Swamp white oak trees provided more benefits than Northern red oak trees ($p < 0.001$) (Figure 17). IGF trees provided more benefits than CG ($p < 0.001$) trees, while CG trees provided significantly less benefits than B&B trees. IGF trees yielded greater benefits than B&B trees but not significantly ($p = 0.09$) (Figure 18).

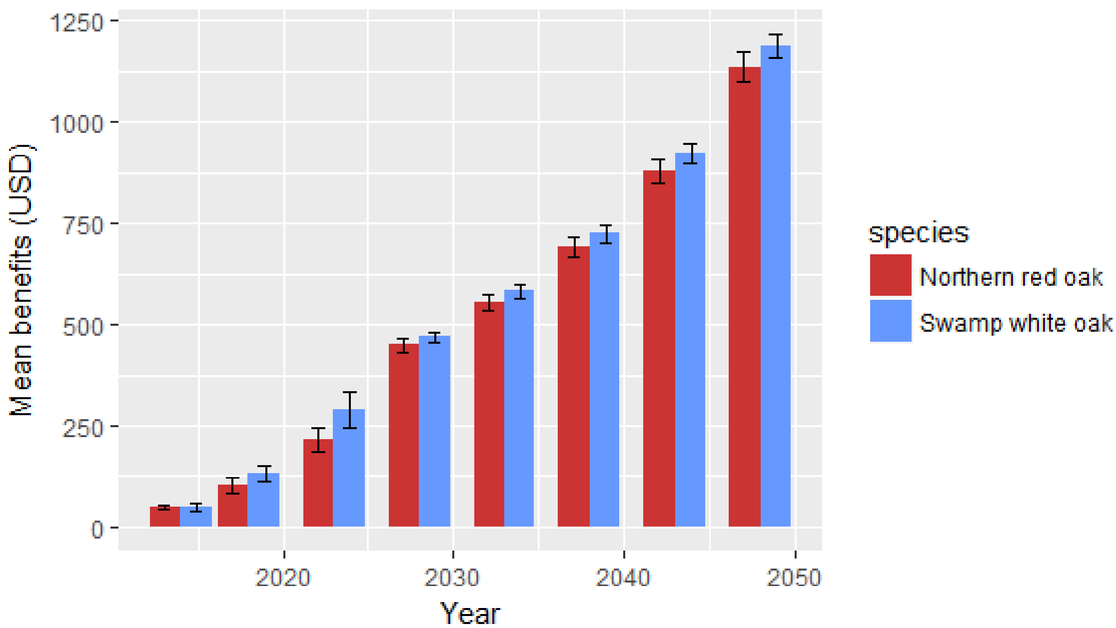

Figure 17. Average benefits, in U.S. dollars, provided by two tree species, Northern red oak (*Quercus rubra*) and swamp white oak (*Quercus bicolor*), during years 2014, 2018, 2023, 2038, 2043, and 2048 based on i-Tree Eco v6.0 estimates of ecosystem services. Error bars represent 95% confidence intervals.

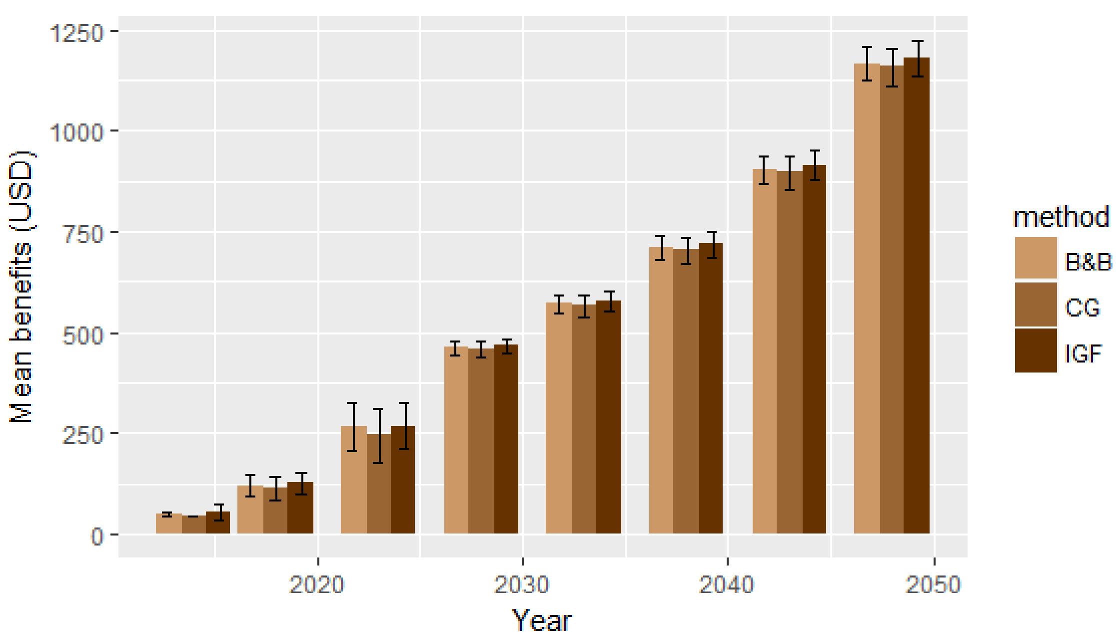

Figure 18. Average benefits, in U.S. dollars, provided by trees from three different nursery production methods, balled and burlapped (B&B), container grown (CG), and in-ground fabric (IGF), during years 2014, 2018, 2023, 2038, 2043, and 2048 based on i-Tree Eco v6.0 estimates of ecosystem services. Error bars represent 95% confidence intervals.

Breakeven point

After fitting a loess curve to the NPV of total benefits and adding a horizontal line to represent where cash flow becomes net positive (NPV = $0.00), the breakeven point was estimated just beyond timestep four (Figure 19), which corresponds to the year 2018.

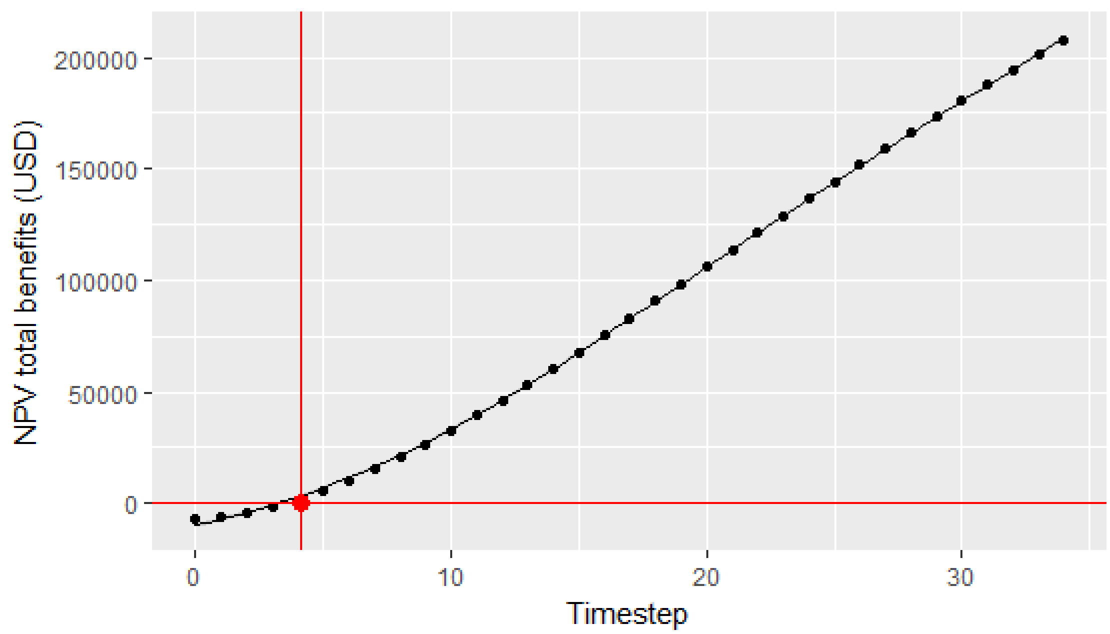

Figure 19. Breakeven point (red) at approximately timestep four for a cost-benefit analysis of 32 street trees in South Amherst, MA. Total benefits, in U.S. dollars, were derived from i-Tree Eco v6.0 estimates of ecosystem services. Net present value (NPV) was calculated using a 5% discount rate. The breakeven point occurs where the fit curve intersects the red horizontal line representing a shift to positive cash flow (NPV = $0.00).

Discussion

Reflecting our results, McPherson et al. (2011) found that aesthetic and other benefits, which are termed “structural” values” in i-Tree, comprised most of the monetary return. These compensatory values are based on tree and landscape appraisal methods, which incorporate trunk area, species, condition, and location to determine replacement values (i-Tree 2017; Nowak et al. 2008). Since i-Tree’s estimated structural values were often much lower than known purchase costs for the trees in this system, compensatory values were likely underestimated. These trees were too far (>60 ft) away from buildings to provide energy savings, and similarly, they offered no benefits from carbon avoided.

There are a variety of potential inaccuracies and limitations that come with modeling ecosystem services and associated benefits using i-Tree tools. Not fully captured here were replacement costs due to mortality and continued planting efforts. This was overlooked primarily because it would be too difficult to model tree loss over time, while accounting for trees entering the system at 2 in. caliper (with DBH approximating average size at timestep 0) to replace much older, larger individuals. Maintenance was not included in the costs for this system either, though that is more easily explained; since these trees are planted in public rights-of-way, positioned far enough off the road and away from sidewalks, there is minimal to no maintenance required. Pruning would typically be suggested but is perhaps unnecessary for this system, as these trees have yet to be pruned since planting. While the trees in this system are unique in this way, costs associated with maintenance, or lack thereof, would be relevant for most street trees (Vogt et al. 2015).

With these limitations in mind, it is important to consider broader implications suggested by these results. Planted in 2014, this system of street trees reached its breakeven point in 2018, when benefits from ecosystem services paid back initial costs of purchasing and planting. By 2023, the average tree, regardless of species or nursery production method, will be worth more in annual benefits than initial costs, and by 2048, an individual tree will be providing nearly $1200 in benefits. IGF trees will provide greater benefits than B&B trees, while CG trees will offer the least ecosystem services. These findings reflect differences in growth observed in Chapter 2 and should be considered in combination with those results. Though model outputs from i-Tree are coarse, the economic values generated are robust enough to make the case for urban greening efforts based on the time it takes for return on investment, and more stock should be taken regarding the role of nursery production method in street tree selection.

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CHAPTER 4

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

It is well-known and further evidenced by this research that trees offer a suite of ecosystem services, which people and wildlife benefit from, especially in the urban environment. Some of those services, such as aesthetic and social benefits, are more difficult to quantify, pointing to gaps that exist in both knowledge and research, as well as tools for analyzing the urban forest. Structural and related compensatory values begin to capture these benefits but are likely underestimating them; nursery retail prices could perhaps serve as proxies, though they do not capture willingness to pay for street trees over the long-term, beyond initial planting.

In contrast to urban forest benefits, we have acknowledged that street trees require investment and often incur costs for maintenance and replacement over time. Risk of personal injury and property damage, either of which can be caused by trees and the wildlife they attract, are not accounted for in most urban forest cost-benefit research. Other urban forest disservices and potential costs, in some instances, include obscured views, allergens, pests and insects, and landscape clean-up (Escobedo et al. 2011). Along with perceptions of ecosystem services, awareness and sensitivity to risks and disservices will vary by person and location, reiterating the mantra, right tree, right place.

There is a common Chinese proverb that states, "The best time to plant a tree was 20 years ago. The second best time is now." While this certainly applies to rural forests, planting street trees is not always beneficial. Regions where water resources are scarce or colder climates are experienced (i.e., where shading and cooling provided by trees might be undesirable) might be less sensible candidates for increased urban tree planting. Increased risk for gentrification in areas with low socio-economic demographics would also not be an ideal outcome of urban greening, potentially exacerbating issues of environmental justice. Given the strong associations between wildlife and oak trees, conflict surrounding urban wildlife should be considered. Though wildlife is widely appreciated by residents (Krester et al. 2009), nuisance animals and various levels of wildlife acceptance capacity (Decker and Purdy 1988) can exist across the urban landscape. Increased abundance of prey species (e.g., small mammals) in response to acorn mast can also increase predator populations. With these potential drawbacks in mind, both the abundance and distribution of oak trees should be taken into account when planning for street tree installment.

Recent research considering massive urban tree planting efforts occurring across the U.S. examined whether these "million tree" campaigns are successful in establishing street trees and ensuring urban forest benefits. Work by Ko et al. (2016), among others, suggested that mortality may undermine tree planting. Unless street trees are monitored and maintained, performance and survivability (and thus, benefits) may not be achieved. Given these doubts in our understanding and quantification of the urban forest, it is important to thinking critically about not only species and nursery production method, but where and when street tree planting is most appropriate or, in this case, beneficial.

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